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Unburned mixture fingers in premixed turbulent flames

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Abstract

Data obtained in 3D direct numerical simulations of statistically planar, 1D premixed turbulent flames indicate that the global burning velocity, flame surface area, and the mean flame brush thickness exhibit significant large-scale oscillations with time. Analysis of the data shows that the oscillations are caused by origin, growth, and subsequent disappearance of elongated channels filled by unburned gas. The growth of such an unburned mixture finger (UMF), which deeply intrudes into combustion products, is controlled by a physical mechanism of flame-flow interaction that has not yet been highlighted in the turbulent combustion literature, to the best of the present authors knowledge. More specifically, the fingers grow due to strong axial acceleration of unburned gas by local pressure gradient induced by heat release in surrounding flamelets. Under conditions of the present DNS, this physical mechanism plays an important role by producing at least as much flame surface area as turbulence does when the density ratio is equal to 7.5. Although, similarly to the Darrieus-Landau (DL) instability, the highlighted physical mechanism results from the interaction between a premixed flame and pressure field, it is argued that the UMF and the DL instability are different manifestations of the aforementioned interaction. Disappearance of an UMF is mainly controlled by the high-speed self-propagation of strongly inclined flame fronts (cusps) to the leading edge of the flame brush, but significant local increase in displacement speed due to large negative curvature of the front plays an important role also.

Keywords: Premixed turbulent flame; Physical mechanisms; Darrieus-Landau instability; DNS; Modeling

1. Introduction

In recent 3D Direct Numerical Simulation (DNS) studies [1–4] of statistically planar, 1D, premixed turbulent flames, the following phenomenon was documented. Both turbulent burning velocity U_t and mean flame brush thickness δ_t, evaluated by averaging the DNS data over yz-planes, which are parallel to the mean flame surface, exhibit significant large-scale oscillations with time, see Fig. 1 in Section 3. Bell et al. [2] and Poludnenko and Oran [3,4] associated these oscillations with formation of a cusp [5–7], i.e. a highly curved tip of a conical flame surface with

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a small angle, with unburned gas being inside the cone. For instance, Bell et al. [2] attributed the oscillations of $U_t(t)$ to periodical growth of cusps into "elongated channels" filled by unburned gas. Similar structures were documented in experimental studies of premixed turbulent flames, see Fig. 2 in Ref. [8], Fig. 1 in Ref. [9], Figs. 9 and 10 in Ref. [10], Fig. 10 in Ref. [11], Fig. 4 in Ref. [12], Figs. 3, 7 and 12 in Ref. [13], Fig. 4d in Ref. [14], Fig. 4 in Ref. [15], Figs. 2 and 4 in Ref. [16], or Figs. 4a and 10 in Ref. [17].

To the best of the present authors' knowledge, physical mechanisms that control the initiation and growth of the elongated channels have not yet been analyzed. As far as the disappearance of the channels is concerned, Bell et al. [2] have noted "period of apparent rapid movement when the sides of the channel close upon each other and the cusp returns to a more typical position relative to the rest of the flame". Poludnenko and Oran [4] highlighted the rapid propagation of a cusp along its axis by exploiting the classical theory by Zel'dovich [7] and by numerically simulating a cusp formed due to collision of two planar laminar premixed flames that move in almost opposite directions. Formation of isolated pockets of unburned gas, documented in a 2D DNS study by Kollmann et al. [18,19], can also be relevant to the disappearance of the channels, as noted by Bell et al. [2].

The goal of the present work is to analyze DNS data in order to gain further insight into physical mechanisms that control the growth and disappearance of the aforementioned elongated channels.

In the next section, the attributes of the DNS database are summarized. Obtained results are discussed in the third section followed by conclusions.

2. DNS database

Because DNSs addressed here were discussed in detail elsewhere [1,20,21] and the computed data were used in a couple of papers [22–27], we restrict ourselves to a brief summary of the simulations.

The DNSs dealt with statistically planar, 1D, adiabatic premixed flames modeled by unsteady 3D continuity, Navier–Stokes, and energy equations, as well as the ideal gas state equation. The Lewis and Prandtl numbers were equal to 1.0 and 0.7, respectively. The dependence of the molecular transfer coefficients on the temperature T was taken into account, e.g. the kinematic viscosity $\nu = \nu_0 (T/T_0)^{0.7}$. Combustion chemistry was reduced to a single reaction.

The computational domain was a rectangular $\Lambda_x \times \Lambda_y \times \Lambda_z$, with $\Lambda_x = 8$ mm, $\Lambda_y = \Lambda_z = 4$ mm, and was resolved using a uniform mesh of $512 \times 128 \times 128$ points. Homogeneous isotropic turbulence (rms velocity $u' = 0.53$ m/s, integral length scale $L = 3.5$ mm, Kolmogorov scale $\eta = 0.14$ mm, and $Re_t = u'L/\nu_u = 96$) was generated at the inlet boundary, entered the computational domain with a mean velocity U, and decayed along the direction x of the mean flow. The flow was periodic in y and z directions.

At an initial instant, a planar laminar flame was embedded into statistically the same turbulence assigned for the velocity field in the entire computational domain. Subsequently, the inflow velocity was increased at two instants, i.e. $U(0 \leqslant t < t_1) = S_L < U(t_1 \leqslant t < t_2) < U(t_2 \leqslant t)$, in order to keep the flame in the computational domain till the end t_3 of simulations.

Three cases characterized by three different density ratios $\sigma = \rho_u/\rho_b$ were investigated. Here, subscripts u and b designate unburned and burned gas, respectively. Characteristics of these flames are listed in Table 1, where S_L is the laminar flame speed and $\delta_L = (T_b - T_u)/\max|dT/dx|$ is the laminar flame thickness. We will place the focus of discussion on results obtained in cases H and L, characterized by the highest and lowest density ratio, respectively.

Results reported later were obtained for $t \geqslant t_2$, with the instants t_2 being different in cases H, M, and L. Because the mean inlet velocity was constant at $t \geqslant t_2$, no external acceleration affected results obtained in the laboratory coordinate framework. Both time-dependent mean quantities $\bar{q}(t)$ averaged over transverse yz-planes and mean quantities $\langle q \rangle$ averaged also over time interval $t_2 \leqslant t \leqslant t_3$, with $t_3 - t_2 \approx 1.5L/u'$, will be discussed in the next section. Conditioned quantities, e.g. $\langle q | \xi_1 < c < \xi_2 \rangle$, and Probability Density Functions (PDFs), e.g. $P(q, \xi_1 < c < \xi_2)$, reported in the following, were obtained using joint PDFs $P(c, q, x)$, which were computed by processing the DNS data saved for a plane $x =$const at various instants within the time interval $t_2 \leqslant t \leqslant t_3$. Here, $c = (T - T_u)/(T_b - T_u)$ is the combustion progress variable, q is an arbitrary quantity, while $\langle q | \xi_1 < c < \xi_2 \rangle$ is a mean value of q averaged by considering only points $\mathbf{x}$ and instants t such that $c(\mathbf{x}, t)$ is within the interval (ξ_1, ξ_2). The statistical convergence of the DNS data obtained at $t_2 \leqslant t \leqslant t_3$ was shown in earlier papers [20–27].

Table 1
Flame characteristics.

	Case H	Case M	Case L
$\sigma = \rho_u/\rho_b$	7.53	5.0	2.5
S_L, m/s	0.600	0.523	0.416
δ_L, mm	0.217	0.191	0.158
$\langle U_t(t) \rangle$, m/s	1.13	1.00	0.74
$\langle U_t^{2\prime} \rangle^{1/2} / \langle U_t \rangle$	0.10	0.17	0.11
$\langle \delta_t(t) \rangle$, mm	1.23	1.41	1.35
$\langle \delta_t^{2\prime} \rangle^{1/2} / \langle \delta_t \rangle$	0.16	0.29	0.25